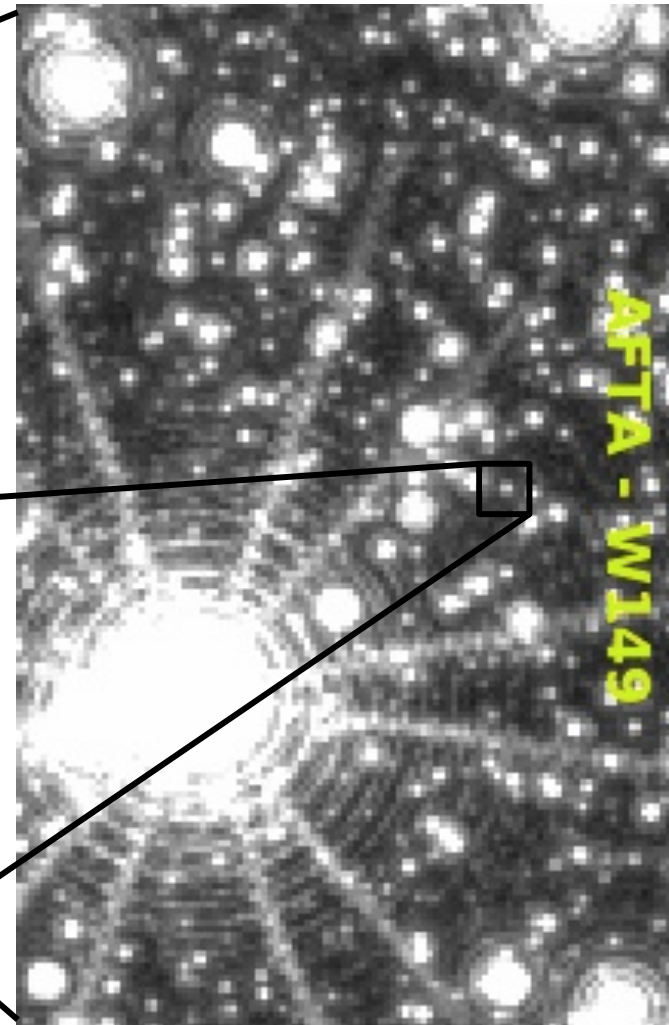
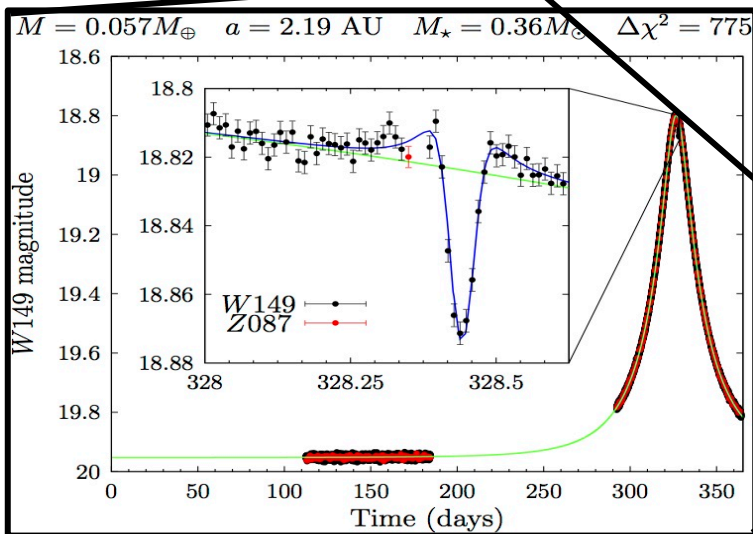
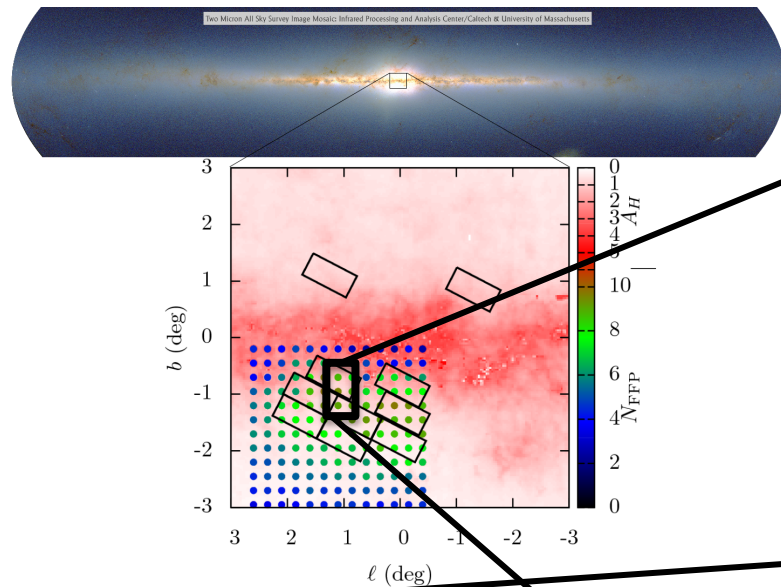


Measuring Parameters for Microlensing Planetary Systems.

Scott Gaudi
Matthew Penny
(OSU)

WFIRST Microlensing Survey.



Microlensing Survey Dataset.

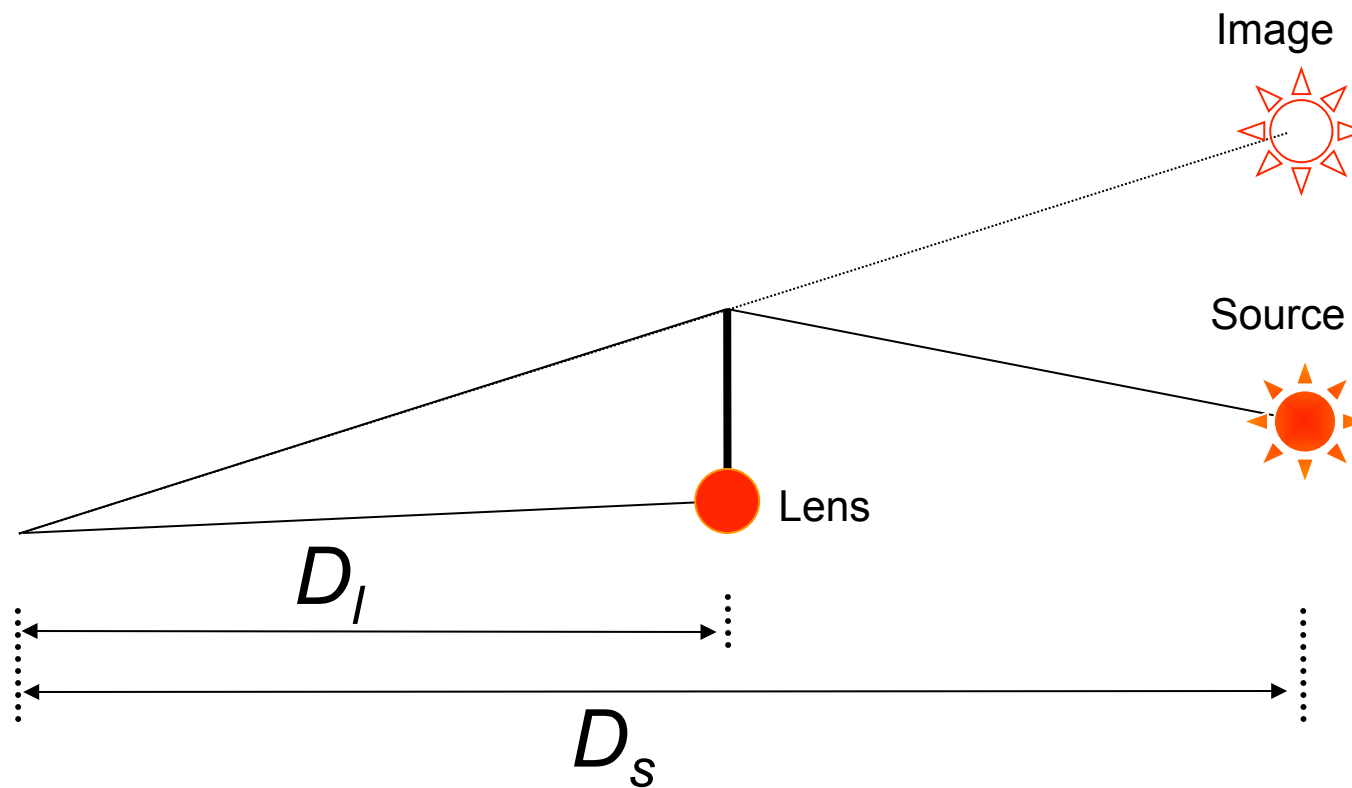
Properties.

- ~3 sq. deg.
- ~432 days.
- ~80% of the area will have 2 million seconds of integration time.
- ~100 million stars down to $J < 22$, with ~40,000 measurements per star (~10% in bluer filter), $N^{-1/2} = 1/200$
- ~20 billion photons detected for a $J=20$ star.
- Deepest IR image ever?

Extraordinarily rich dataset.

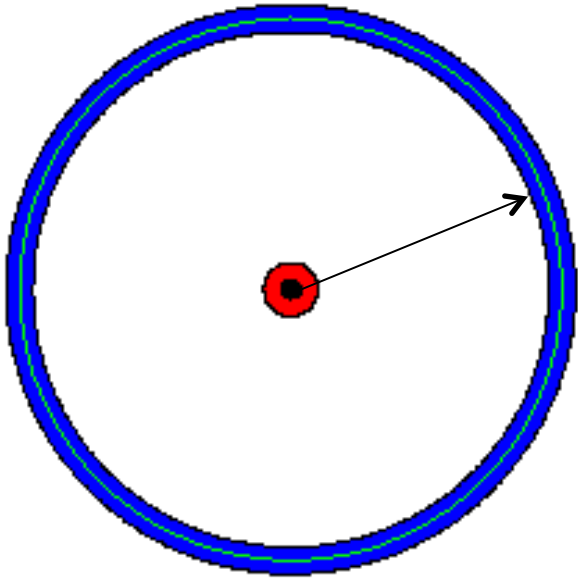
- Measure parallaxes to $<10\%$ and proper motions to <300 m/s ($<0.3\%$) for 10^8 bulge and disk stars.
 - Larger than GAIA.
- Detect dark companions to disk and bulge stars.
- Find $>10^5$ transiting planets (Bennett & Rhie 2002).
- Detect 5000 KBOs down to 10km, with 1% uncertainties on the orbital parameters (Gould 2014).
- Exquisite characterization of the detector.
- ??

Microlensing Basics.



Angular Einstein Ring.

$$\theta_E = \sqrt{\kappa M \pi_{rel}}$$



- Lens mass

$$M$$

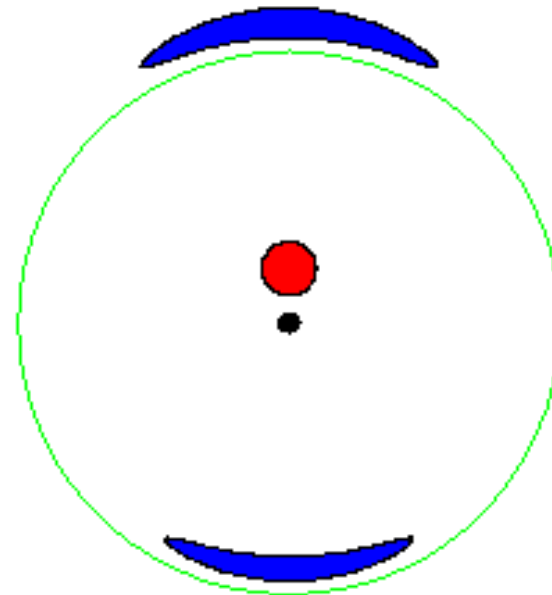
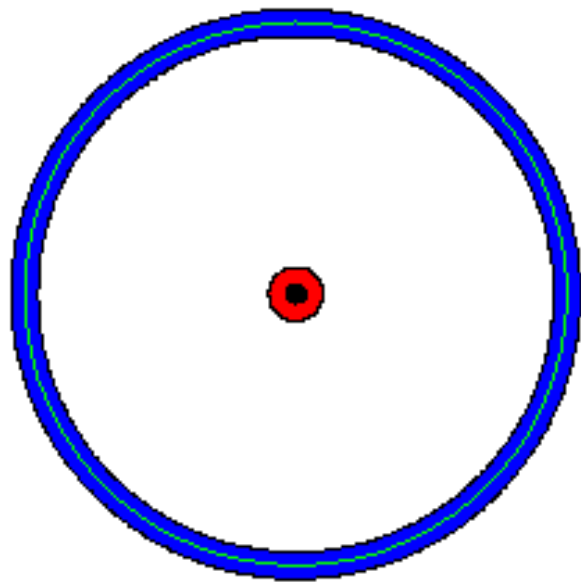
- Relative Lens-Source Parallax

$$\pi_{rel} = \pi_l - \pi_s = \frac{AU}{D_l} - \frac{AU}{D_s}$$

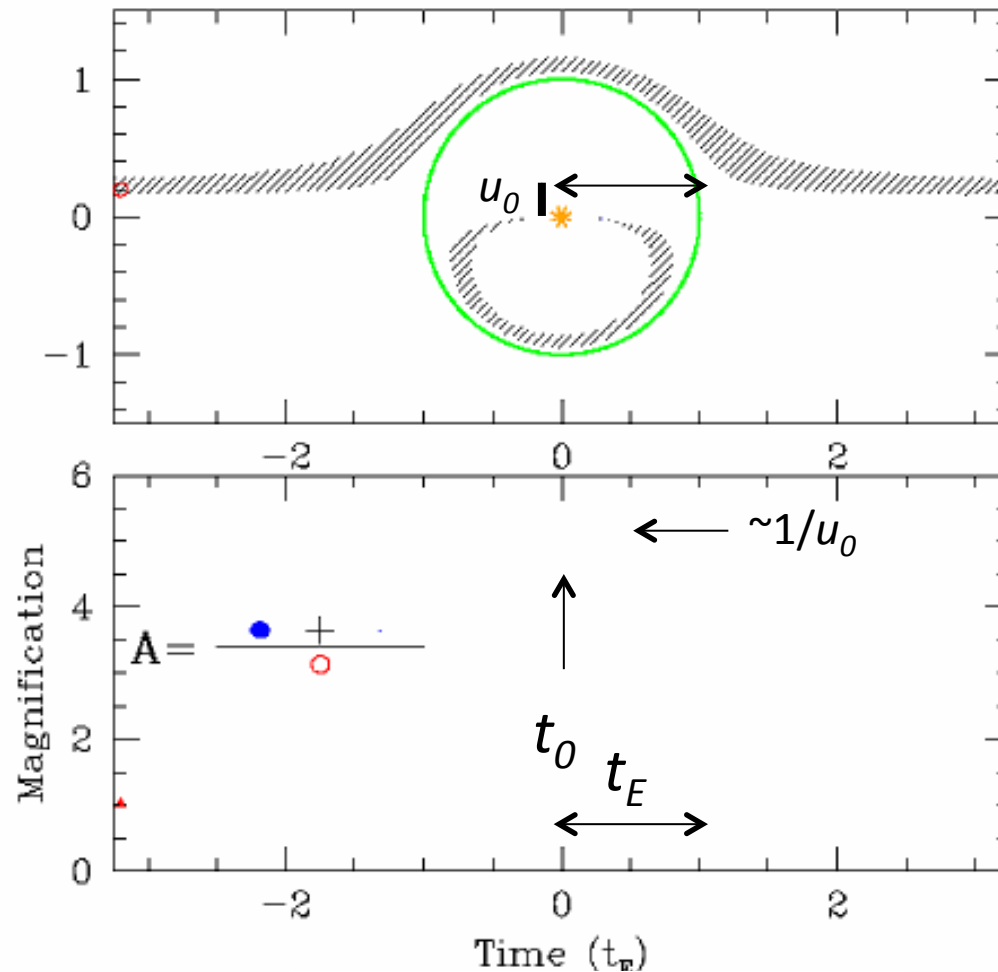
- Constant

$$\kappa = \frac{4G}{c^2 AU} = 8 \text{ mas}/M_{\odot}$$

Rings vs. Images.



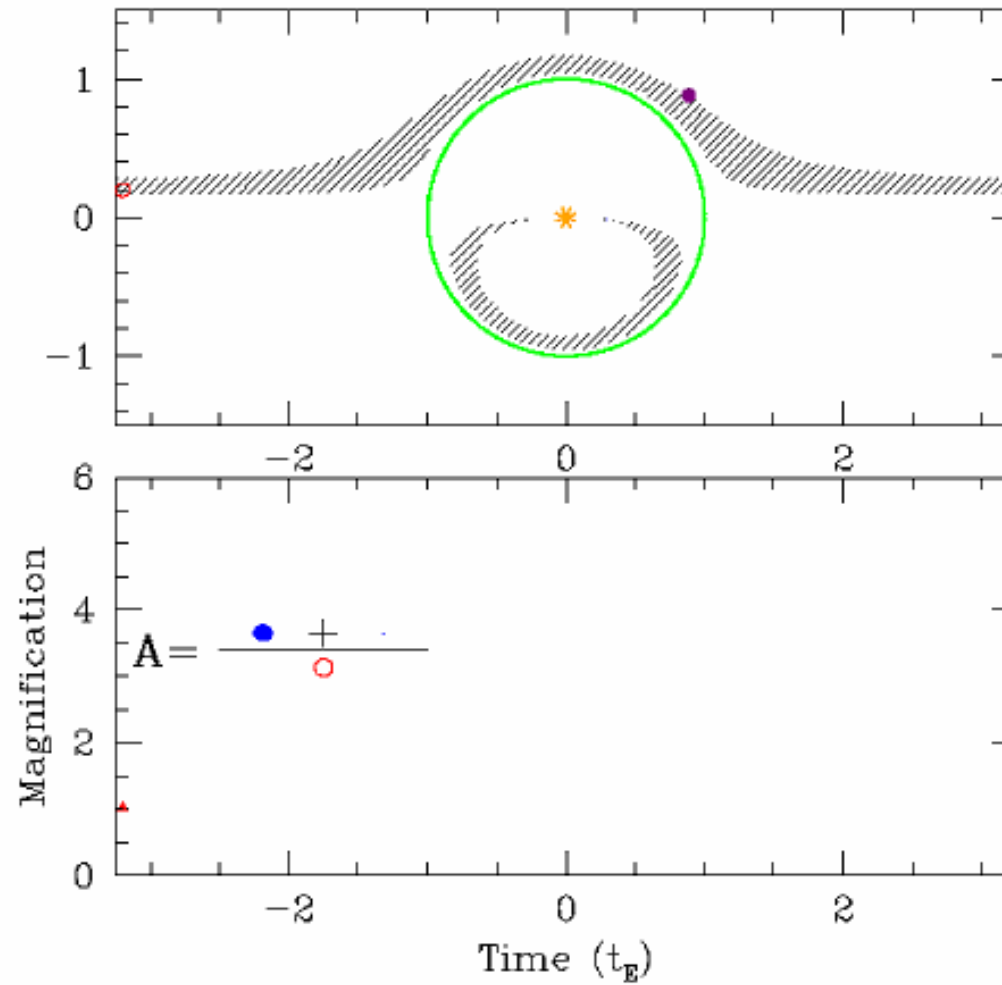
Microlensing Events.

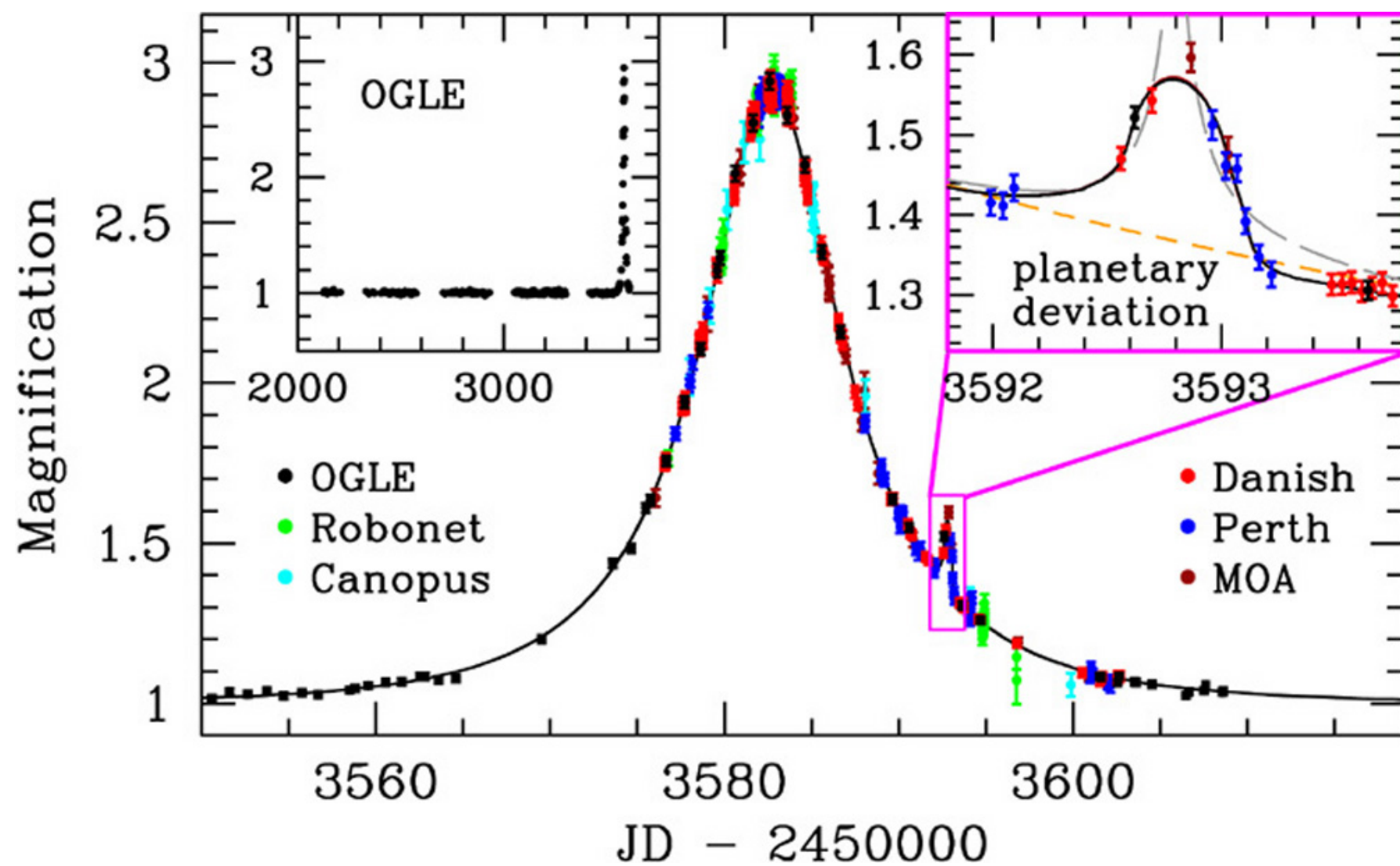


(t_0, u_0, t_E)

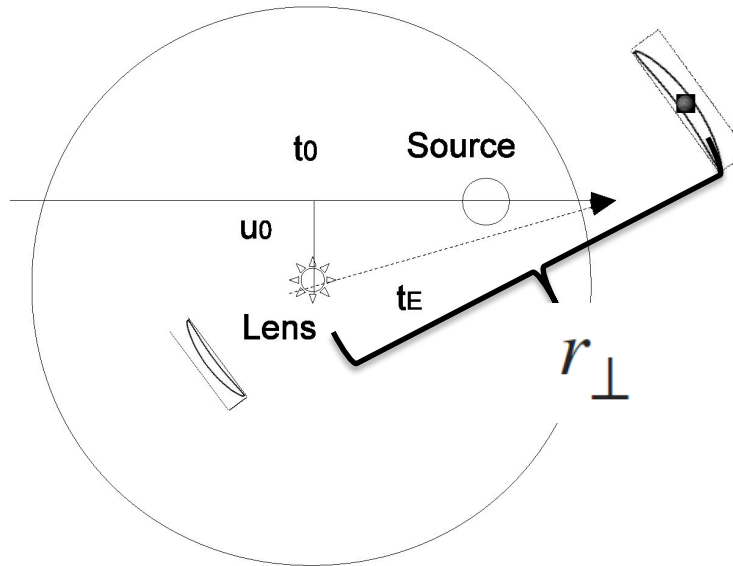
$$t_E = \frac{\theta_E}{\mu_{rel}} = f(M, D_l, \mu_{rel})$$

Detecting Planets.





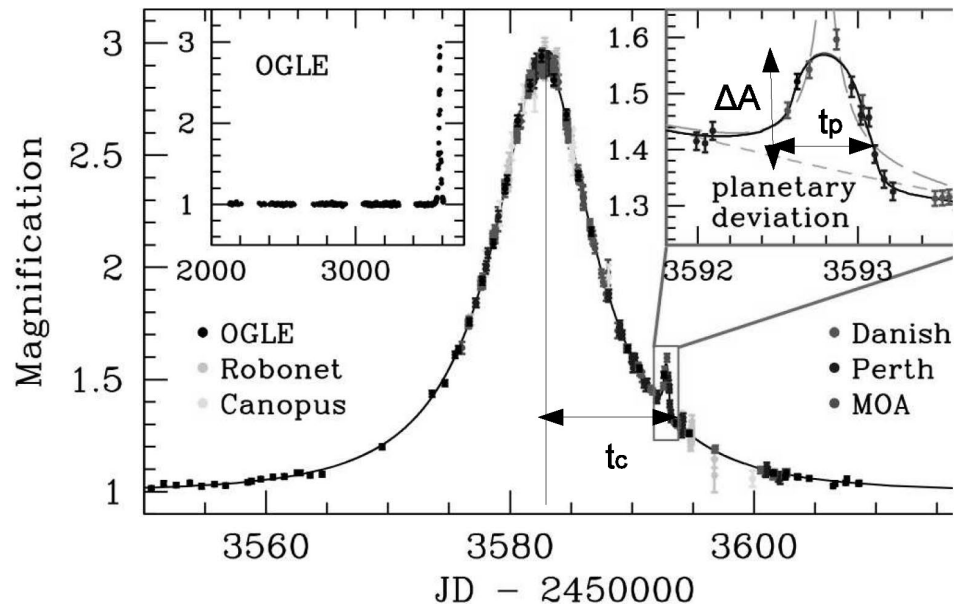
Basic Measurements.



Primary Event:

$$(t_0, u_0, t_E)$$

$$t_E = \frac{\theta_E}{\mu_{rel}} = f(M, D_l, \mu_{rel})$$



Planetary Deviation:

$$(t_p, t_c, \Delta A)$$

$$q = \frac{m}{M} \sim \left(\frac{t_p}{t_E} \right)^2$$

$$s = \frac{r_{\perp}}{\theta_E D_l} = f(t_0, t_c, t_E)$$

All events:

$$t_E, q, s$$

timescale, mass ratio,
dimensionless projected
separation

$$\vartheta_E$$

Angular Einstein
Ring Radius

$$=f(M, D_l)$$

$$\pi_E$$

Microlens Parallax

$$=f(M, D_l)$$

$$F_l$$

Lens Flux

$$=f(M, D_l)$$

combine any two

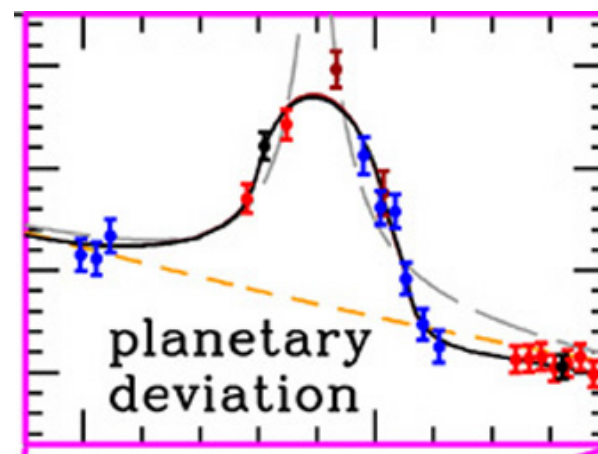
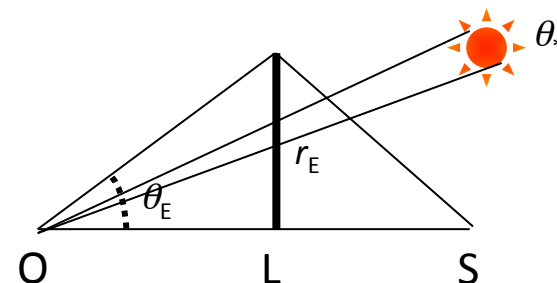
$$M_l, D_l$$

$$m=qM, r_{\text{perp}} = s\vartheta_E D_l$$

Angular Einstein Ring Radius.

- Need an angular ruler.
 - Finite size of source star
 $\rho_* = \theta_* / \theta_E$
 - θ_* from source flux + color
 - Most planetary events.
 - **Need measurements in two filters during the event.**

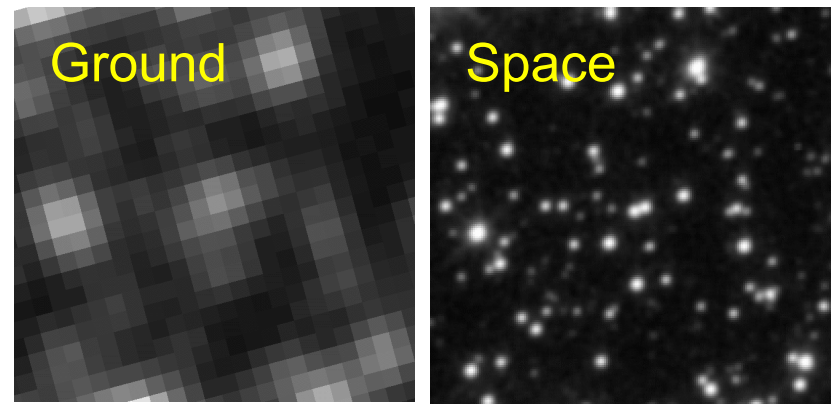
$$\theta_E = f(M, D_l)$$



Lens Flux.

- Need to measure the lens flux.
 - Have to resolve out unrelated stars blended with lens and source.
 - Subtract source flux from sum of lens+source.
 - Remaining flux is due to the lens.
 - **Need angular resolution better than $\sim 0.3''$.**

$$F_{l,\lambda} = \frac{L_\lambda}{4\pi D_l^2} = f(M_l, D_l)$$

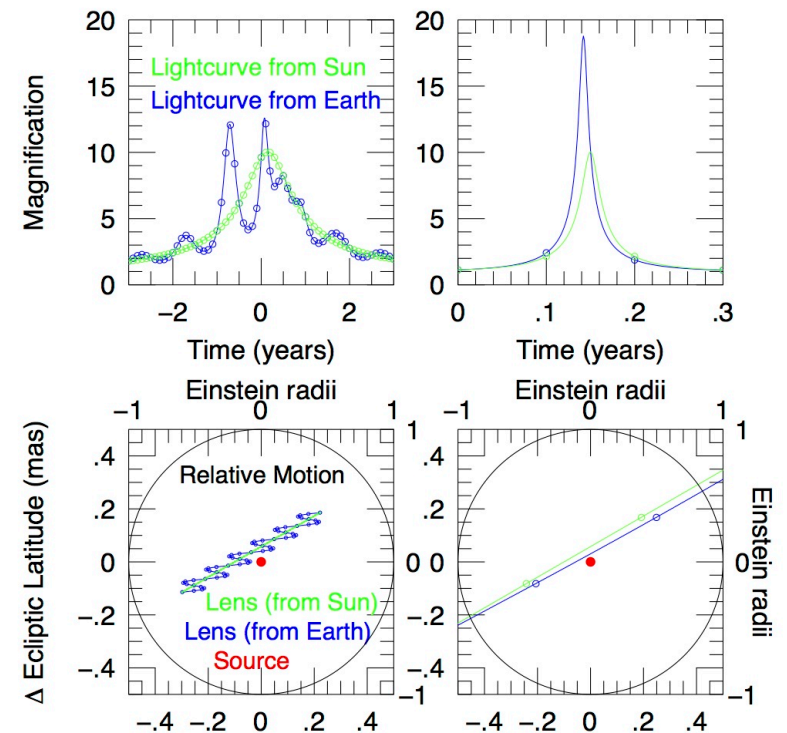


The field of microlensing event
MACHO 96-BLG-5
(Bennett & Rhie 2002)

Microlens Parallax.

- Use the Earth's orbit as a ruler.
 - Microlens parallax is a vector.
 - Direction of relative lens-source proper motion.
 - Measure deviations from a rectilinear, uniform trajectory.
 - Parallax asymmetry gives one component.
 - **Precise lightcurves for most events give one component of parallax.**

$$\pi_E = \frac{\pi_{rel}}{\theta_E} = f(M, D_l)$$



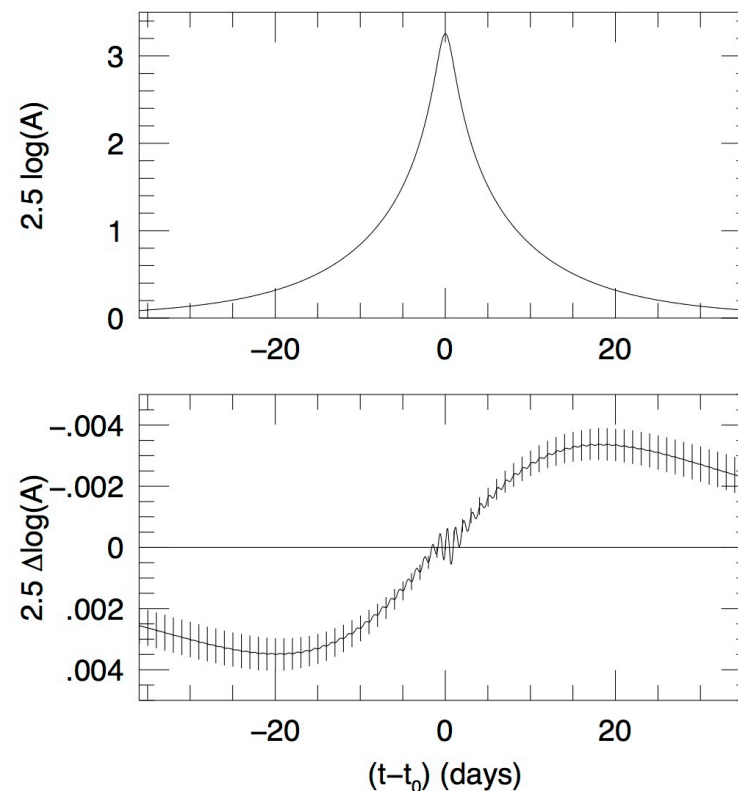
(Gould & Horne 2013)

Other possible measurements.

- Additional parallax measurements.
- Directly measuring relative lens-source proper motion.
- Astrometric microlensing.
- Orbital motion.

Parallax, continued.

- Long timescale events.
 - Both components.
- Geosynchronous parallax (Gould 2013)
 - High magnification events.
- L2-Earth parallax (Yee 2013).
 - JWST+WFIRST Geo, or Earth +WFIRST L2
 - Both components.
 - High-magnification events.
 - Requires alerts or dedicated surveys.



(Gould 2013)

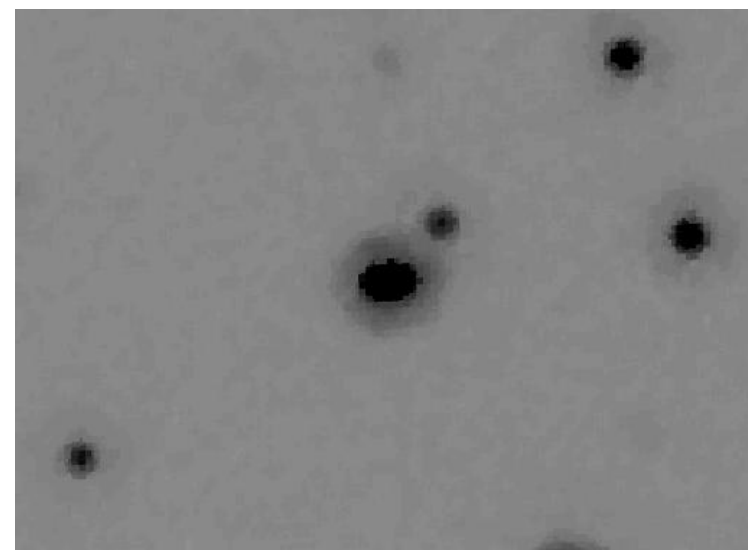
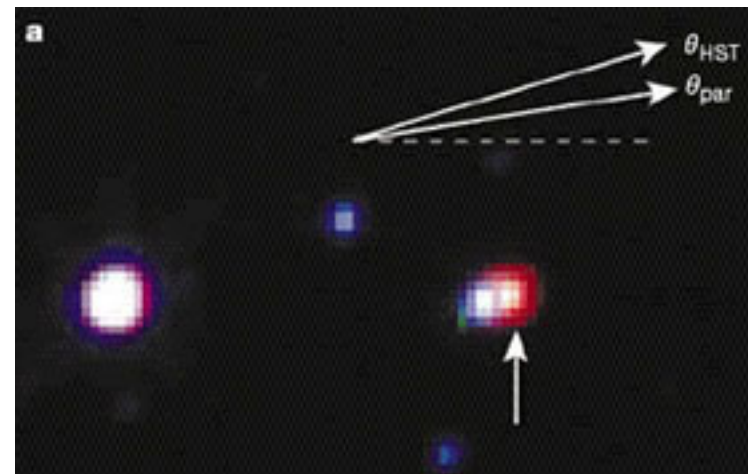
Directly measuring μ_{rel} .

For luminous lenses:

- Direct resolution of lens and source.
 - High μ_{rel} events.
 - Precursor observations now!
- Image elongation.
- Color-dependent centroid shift.

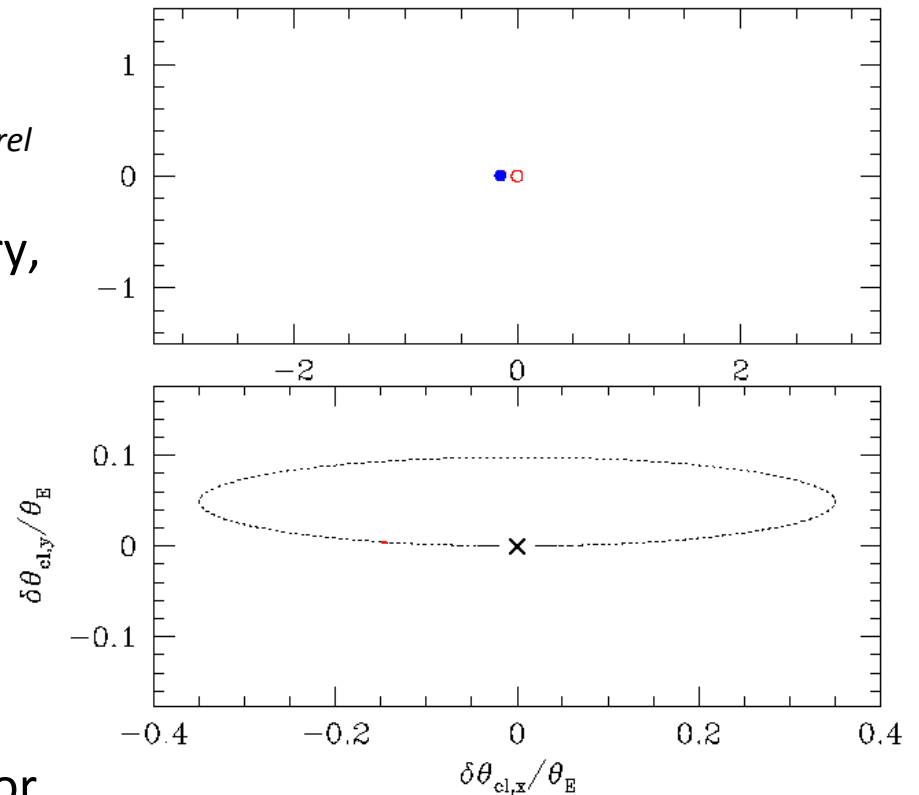
Useful for:

- Testing for companions to lens or source.
- Events where the finite source size is not measured.



Astrometric microlensing.

- Centroid shift of source.
 - Size is proportional to θ_E
 - Orientation is in the direction of μ_{rel} and π_E
 - Combined with parallax asymmetry, get complete solution.
- Can be used to measure masses of isolated remnants and brown dwarfs.
- Very small shift.
 - Worry about systematics.
 - Can be vetted using direct measurement of μ_{rel} from precursor observations.



Summary.

- For planetary deviations with luminous lenses, will get (model dependent) masses.
 - Need two filters during the event.
 - Need high resolution.
- For planetary deviations with non-luminous lenses, will get partial information.
 - Need two filters during the event.
 - Need precise light curves.
- There are a variety of additional measurements we can make for a subset of events.
 - Additional information (orbits).
 - Redundancy to check solutions.
 - Strict control of systematics (photometry + astrometry).
 - ToO and/or Alerts.
 - Precursor observations.

Implications?

- Potentially very rich dataset, for microlensing and non-microlensing science, as well as for calibration of the detector.
- In order to extract the maximum amount of science from this dataset, we need to:
 - Think about what else can be done with this dataset.
 - Understand how and how well it can be used to calibrate the detector.
 - Figure out what additional measurements we might need to make now to maximally leverage this dataset for these purposes.

HST Precursor Survey.

- With HST imaging of (a subset of?) the WFIRST fields in several bluer filters:
 - Can measure metallicities, ages, distances, and foreground extinction for all the bulge and disk stars that will have WFIRST parallaxes and proper motions.
 - Can test proper motion and astrometric microlensing measurements by resolving the lenses and sources of future microlensing events.
 - Can identify and map out unusual stellar populations (blue stragglers, etc.)
 - Can identify the locations and colors of all of the stars in the microlensing fields with higher resolution and fidelity than WFIRST or Euclid.